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## An analysis of clear sky and contextual biases using an operational over ocean MODIS aerosol product

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[1] Clear sky and other cloud-related contextual biases are critical yet unsolved mysteries for aerosol related climatological studies using satellite observations. For the first time, we simulated contextual biases over ocean using 2-years of Navy Aerosol Analysis and Prediction System (NAAPS) products that include the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) assimilation. We compared model-derived AOD in regions with and without observations, and found that sampling results in negligible seasonal globally averaged AOD bias (<5%). Biases are more pronounced in regions with frequent overcast skies and high aerosol loadings, such as Southeast Asia, and mid-latitude South America. This suggests that contextual biases may develop from transport covariance and other observing biases. Lastly, we found that over remote oceans, under cloud decks, a slight increase aerosol optical depth values could exist, comparing with cloud free regions. But this is still small relative to cloud artifacts in the retrieval. **Citation:** Zhang, J., and J. S. Reid (2009), An analysis of clear sky and contextual biases using an operational over ocean MODIS aerosol product, *Geophys. Res. Lett.*, 36, L15824, doi:10.1029/2009GL038723.

### 1. Introduction

[2] The current generation of NASA satellite derived aerosol optical products, such as those from MODIS and MISR, have been widely used in numerous atmospheric and climate related applications [e.g., Remer *et al.*, 2008; Kahn *et al.*, 2005]. However, the majority of optical aerosol particle, gas, and surface retrieval algorithms alike limit their studies to cloud free paths. This clear-sky only approach introduces a suite of biases to the satellite aerosol related studies. For example, as in cloudy regions aerosol plumes and cloud layers could coexist at different altitudes leading to the well known clear sky bias-described as the ratio of clear sky observation to the total mean. Similarly, we can envision a host of sampling biases where observation probability and aerosol optical and physical properties covary, such as with diurnal sampling, surface type, or correlations to specific meteorological features. These types of biases where observation ability or uncertainty covary with extensive aerosol properties such as concentration, optical depth or aerosol type can be described as “contextual biases”, and lead to another

layer of uncertainty in our understanding and assimilation of aerosol properties into models [Zhang *et al.*, 2008].

[3] The purpose of the investigation presented here is to semi-quantitatively derive the nature of some aerosol contextual biases put forth by Reid *et al.* [2004] globally. In that paper, they identified a region of satellite under-sampling off the coast of South America by ratioing Navy Aerosol Analysis and Prediction System (NAAPS) aerosol optical depths (AOD) where MODIS data was available to all model data. Smoke appeared to be preferentially transported along frontal features where clouds are likely to occur, forming an aerosol-transport mechanism covariance and a likely underestimate of aerosol burden. From this, they hypothesized that satellites were not observing major smoke transport pathways over the Atlantic Ocean. Whereas this method can be considered qualitative, with the addition of AOD data assimilation [Zhang *et al.*, 2008], a global analysis can now be undertaken with more support. Indeed, as shown by Zhang *et al.* [2008], AOD quality assurance and data assimilation dramatically improve aerosol forecasts several days out, giving more confidence to periods where aerosol particles are transported into or through cloudy regions. This method cannot be fully quantitative with respect to aerosol particle mass and number concentrations due to uncertainties caused by non-linearities in such factors as particle size and hygroscopicity. However, here we identify regions over the globe where the proper way to interpret aerosol remote sensing data may require further investigation.

### 2. Data and Model

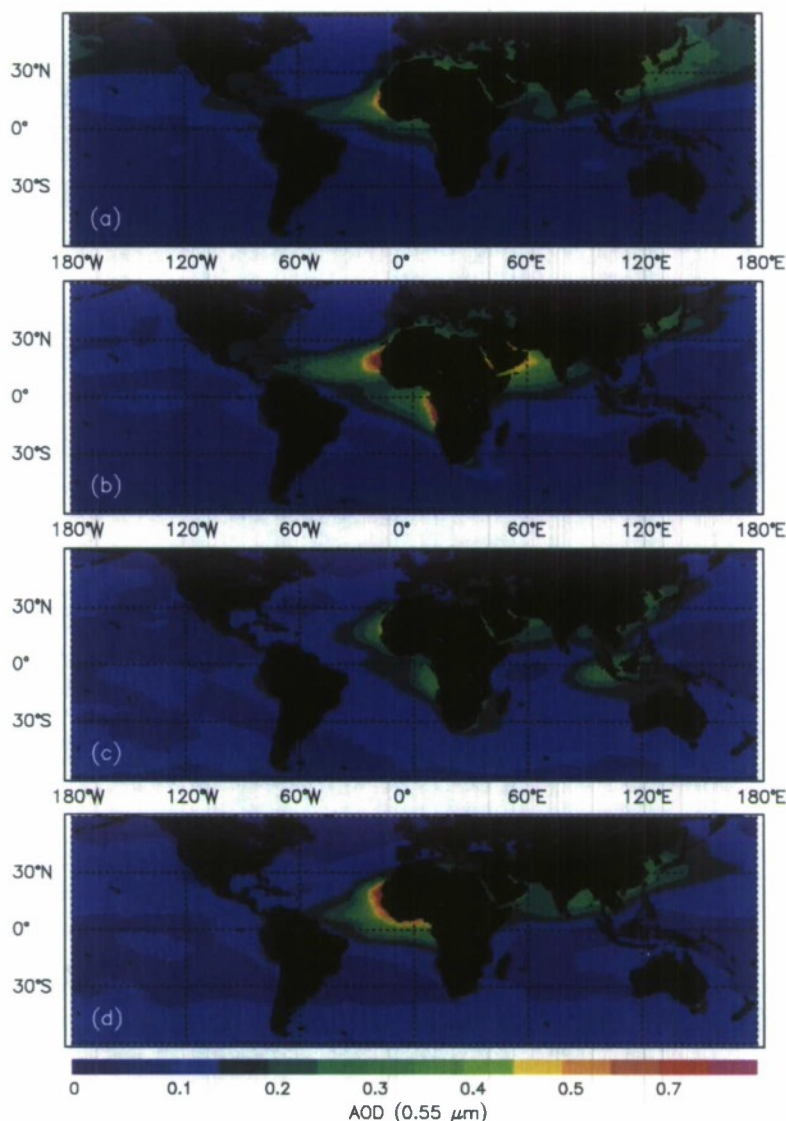
[4] The current operational MODIS aerosol products (collection 4 & 5, MOD04 & MYD04 for Terra and Aqua, respectively), report AOD values at 6 wavelengths ranging from 0.4 to 1.2  $\mu\text{m}$  over global oceans [Remer *et al.*, 2008]. In this study, we assimilated two years of MODIS aerosol products (March 2006–Feb. 2008) into the NAAPS model to compare AOD in regions with and without observations. Given the continuous innovation of data into the model and subsequent improvement in the forecast, we expect a better estimate of aerosol burdens when aerosol particles are advected into regions with clouds at different levels (say aerosol particles advected over stratus or into frontal zones where the phase speed is different from the flow speed).

[5] NAAPS is the U.S. Navy’s operational global aerosol and visibility forecast model. It produces 6-day forecasts four times a day with  $1 \times 1$  degree resolution at 30 levels. Four aerosol species and one gas specie are currently modeled: Dust, sea salt, biomass burning smoke, sulfate, and  $\text{SO}_2$ . The NAAPS operational AOD data assimilation package is based on a 2D-Var NRL Atmospheric Variational Data Assimilation System-AOD (NAVDAS-AOD) [Zhang *et al.*,

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**Figure 1.** Seasonally averaged NAAPS 24-h forecasts (AOD, or  $\tau$ ) for the northern hemispheric (a) Spring (MAM), (b) Summer (JJA), (c) Fall (SON), and (d) Winter (DJF).

2008]. As input, a specially derived and corrected quality controlled MODIS level 3 product was developed specifically for use in data assimilation systems [Zhang and Reid, 2006]. Our study suggested that the overall correlation between NAAPS analysis and AERONET observations is comparable to that of the satellite aerosol products themselves [Zhang *et al.*, 2008], and only slight increase in RMS error over 48 hours (<20%).

[6] Using the assimilated NAAPS data from March 2006 to Feb. 2008, we examined the cloud and sampling related biases in the collection 5 level 2 MODIS aerosol products by studying the differences in the NAAPS aerosol optical depth fields for all skies versus cloud free skies as observed by MODIS. In this study, NAAPS 24 hour (24-h) forecasts (assimilation + 24 hours of natural run) were used instead of the NAAPS analysis. This is because we expect a more objective analysis by comparing NAAPS 24-h forecasts with the NAAPS forecast over cloud-free skies as identified by the MODIS + 1 day's data (different cloud and aerosol fields

from what included in the assimilation process). This said, our results below appear robust even when only analyses were used, as we compared results from 2006 (Mar. 2006–Feb. 2007) to 2007 (Mar. 2007–Feb. 2008). This gives us confidence that the patterns presented are not simply an artifact of model forecast bias.

### 3. Results and Discussions

#### 3.1. Overall Clear Sky and Sampling Bias

[7] Figure 1 shows the seasonally averaged spatial distribution of 24 hour forecast NAAPS AOD over regions that have valid MODIS aerosol retrievals ( $AOD_{modis}$ ), for example over cloud/glint free skies, for Northern Hemisphere spring (MAM, 2006, Figure 1a), summer (JJA, 2006, Figure 1b), fall (SON, 2006, Figure 1c) and winter (DJF, Dec 2006, Jan. and Feb. 2007, Figure 1d). To create Figure 1, for each season, we first binned the collection 5 Aqua and Terra level 2 operational MODIS aerosol products into



6-hour averages of  $1 \times 1^\circ$  Lat/Lon gridded products. The 6-hour averages were created using MODIS data that are within  $\pm 3$  hour of each of the NAAPS runs at 00:00, 06:00, 12:00, and 18:00 UTC. No data filtering process was applied (here we tried to simulate the best scenario when all MODIS aerosol retrievals are used in the analysis). Then, we masked NAAPS 24-hour forecasts (in  $1 \times 1^\circ$  Lat/Lon grid) with the gridded MODIS product, and only using NAAPS 24-hour forecasts over regions that have valid grid-averaged MODIS AOD values. By doing so, we are simulating production MODIS observed aerosol skies using NAAPS 24-h forecasts. If we were to use the more stringent assimilation grade product a significant percentage of retrievals would be filtered out through quality check and quality assurance procedures, and thus introduce a much larger sampling biases than those presented here.

[8] The NAAPS 24-h forecasts shown in Figure 1 were initialized using NAAPS analyses at 0-h. In the process of deriving NAAPS analyses through data assimilation, the quality assured collection 4 MODIS aerosol retrievals [Zhang and Reid, 2006] were used. Notice that although we are studying the clear sky bias of the collection 5 MODIS aerosol product (using it to identify regions with validate collection 5 retrievals only), the quality assured collection 4 MODIS aerosol product is currently included in the data assimilation process. This step is necessary because large retrieval biases can exist regionally in the MODIS aerosol data over ocean, and by using the best quality MODIS aerosol retrievals [Zhang and Reid, 2006] in the assimilation runs, we attempt to separate the contextual bias from the retrieval bias. Also, the quality assured collection 4 MODIS aerosol products were used instead of the collection 5 MODIS aerosol products simply because the quality assurance procedures for the collection 5 MODIS aerosol products are currently under-development. Nevertheless, only small changes were made to over ocean retrievals from the collection 4 to 5 products [e.g., Remer *et al.*, 2008].

[9] Figure 1 demonstrates the well known regions of the world with high aerosol loadings: For all four seasons dust and smoke are prevalent in coastal China, dust off the northwest coast of Africa, pollution and dust in the Indian Bay of Bengal, and dust and pollution over the Arabian Sea. Smoke plumes are also observed over Central America during spring, dust over Mediterranean Sea during winter and spring, smoke off of central Africa and Southeast Asia during summer and fall seasons.

[10] Seasonally averaged spatial distributions of NAAPS AOD over all skies ( $AOD_{all}$ ) were generated and we estimated the global and seasonally averaged observation bias ratio ( $f_r$ ) of  $AOD_{modis}$  to  $AOD_{all}$  as shown in Figure 2 for the same four seasons as Figure 1. As a comparison, Figures 2e–2h show the number of valid MODIS retrievals (Terra + Aqua) used to create Figures 2a–2d. The number of data entries represents the total number of available 6-hour averages for any given  $1 \times 1^\circ$  Lat/Lon grid. Regions that have no MODIS aerosol retrievals for a whole month were not included in the analysis.

[11] For every season, the global averaged  $f_r$  over global oceans is almost unity-suggesting on a global average there does not appear to be a significant AOD sampling bias. In fact, we did not find a significant bias even for the monthly averaged  $f_r$  over global oceans either. This result suggests

that cloud and sampling related biases are small (less than 5%) for the global averaged monthly means using the combined MODIS Aqua and Terra aerosol products.

[12] From Figure 2 this finding is clearly a consequence of slight offsetting regional averages of  $\pm 10$ –15% in the tropics and mid-latitudes, respectively. Such a result is not surprising as in the tropics, the high bias is predominately right along the ITCZ where aerosol particles will no doubt be wet scavenged during cloudy periods (Although, it is noteworthy that this region also has few data samples to assimilate and heavily represents bias as predicted from the free running model). In the mid-latitudes, smoke and pollution aerosols are advected behind frontal systems (see analysis below). Statistics are robust, with larger biases being observable in regions with adequate sampling.

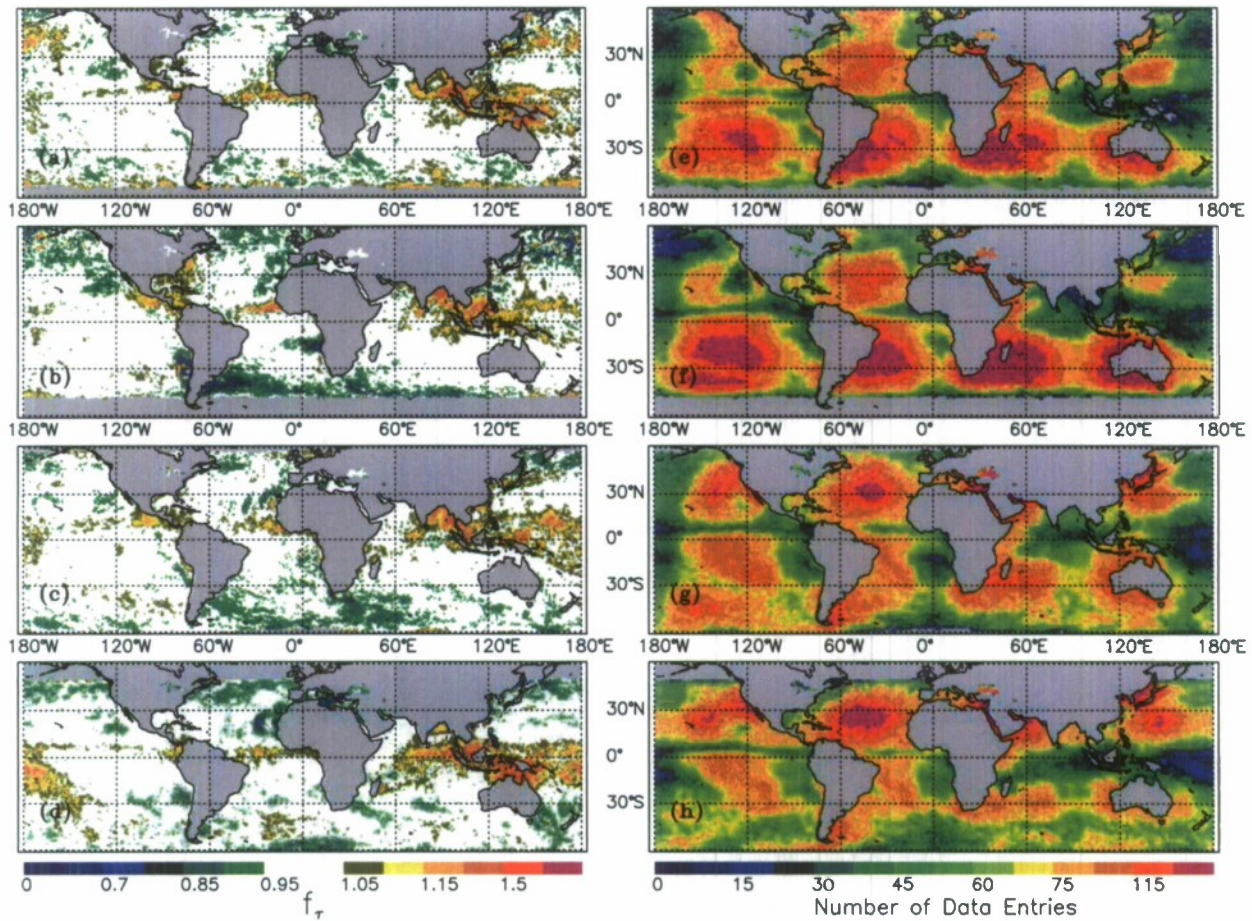
[13] We can analyze our findings further in aerosol prevalent regions and where the biases are more significant ( $\sim \pm 10$ –30%, indicated by orange, red, deep green/blue, respectively). Table 1 summarizes  $f_r$  over 10 selected regions: northwest coast of Africa (NAF); Indian Bay of Bengal (IBB); Coastal China (CHN); Central America (CAM); Arabian Sea (ARS); Mediterranean Sea (MED), Southwest coast of Africa (SWAF), Southeast coast of America (SCA), Southeast coast of Africa (SEAF), and Southeast Asia (SEA); as well as for the global averages for four seasons. Two years (2006: March 2006–February 2007, and 2007: March 2006–February 2007) analyses are included. From Figure 2 and Table 1 we found typically regional biases exist even for the seasonal average on the order of  $\pm 10$ –20%.

[14] Areas of note include: a) South East Asia and Indonesia: high  $f_r$  values of 1.1–1.2 throughout the four seasons for both 2006 and 2007, largely due to poor data sampling rate and high variations of aerosol optical properties over the region; b) India Bay of Bengal: high  $f_r$  values with the maximum value of 1.11 and 1.14 were found in 2006 and 2007, respectively, in all four seasons, similar to the reason as South East Asia; c) Mediterranean Sea: Low values of 0.9 for spring and winter of 2006/2007 likely do to frontal activity; d) Southwest coast of Africa, Southeast coast of Africa, and Southeast coast of America, show low  $f_r$  values during summer of 2006 and 2007 mostly due to advection of smoke over cloud systems (e.g., Figure 3). For example, over Southwest Africa for summer of 2006/2007 both have a 7–8% average low bias due undoubtedly from the advection of smoke over the Namibian stratus deck. In the following three sub sections, we present illustrative examples of the processes at work.

### 3.2. Transport Covariance Over the Remote Southern Oceans

[15] Corresponding to the Aug–Oct burning seasons in South America and Africa (Figure 2b), two low  $f_r$  strips are found over the southern oceans, representing negative sampling biases on the order of  $-20$ –30%. One low  $f_r$  strip starts from the southeast coast of South America and extends to the high latitude southern oceans, and the other strip extends from the west to the east along the south part of Africa. Examination of two years of data confirms Reid *et al.*'s [2004] hypothesis of undetected transport of smoke behind and within frontal system, forming the so-called transport covariance with cloud cover. As an example, Figure 3 shows the RGB true color image of South America and South Africa





**Figure 2.** Seasonally averaged observation bias ratio ( $AOD_{MODIS}/AOD_{all}$ , or  $f_r$ ) for the northern hemispheric (a) Spring (MAM), (b) Summer (JJA), (c) Fall (SON), and (d) Winter (DJF). (e–h) Similar to Figures 2a–2d, but for number of data entries for each gridded  $1 \times 1^\circ$  Lat/Lon grid.

from the Aqua MODIS for August 16, 2006. Over plotted in contour lines are the daily averaged total AOD values from the NAAPS 24-h forecast for the same day. The red and green dots in Figure 3 represent GOES and MODIS hot (fire) spots respectively [e.g., *Prins et al.*, 2001]. As indicated by the NAAPS 24-h forecast, biomass burning aerosol plumes originated from inland South America are transported to the Atlantic oceans, along the frontal cloud system. Similarly,

smoke plumes originated from South Africa are transported to both the Atlantic and Pacific oceans, along with the cloud system. Aerosol plumes can also be seen around the edges of the frontal cloud systems in the MODIS true color image. Lastly, this image demonstrates the advection of smoke over the Namibian stratus fields.

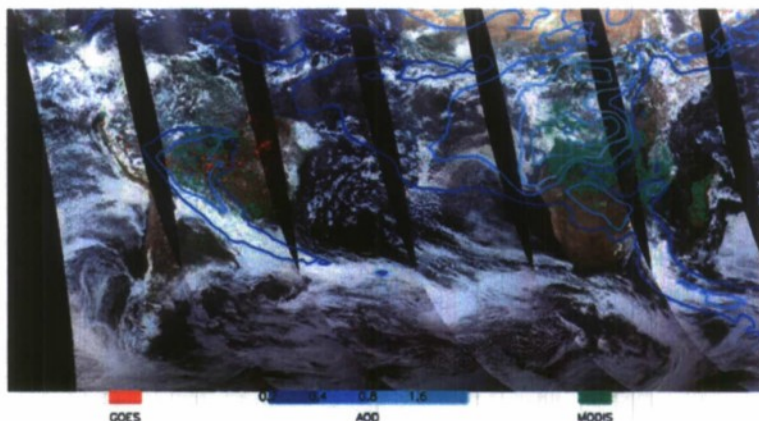
[16] The findings of this simulation are similar in nature although not as strong as the 2001 seasonal case of  $-40\%$

**Table 1.** Sample Bias Ratios ( $f_r$ ) Values for Selected Regions for the Two Year Period<sup>a</sup>

	Latitude ( $^\circ$ )	Longitude ( $^\circ$ )	$f_r$ Spring	$f_r$ Summer	$f_r$ Fall	$f_r$ Winter
NAF	15°S–20°N	40°W–10°E	1.03/1.04	1.00/0.99	1.02/1.04	1.01/1.02
IBB	10°N–30°N	60°E–100°E	1.07/1.05	1.11/1.14	1.10/1.13	1.04/1.06
CHN	20°N–50°N	120°E–150°E	1.02/0.97	1.00/1.04	1.03/1.02	0.97/0.97
CAM	15°N–30°N	110°W–70°W	1.04/1.04	1.07/1.07	1.04/1.07	1.01/1.02
MED	30°N–45°N	0°–40°E	0.92/0.91	0.99/1.00	0.97/0.97	0.91/0.92
ARS	10°N–30°N	30°E–60°E	0.99/1.00	1.02/1.02	1.00/0.99	0.99/0.99
SWAF	20°S–0°N	0°–20°E	1.00/1.04	0.92/0.93	0.99/1.05	1.00/1.00
SCA	50°S–30°S	70°W–40°W	0.97/0.95	0.88/0.96	0.94/0.94	0.97/0.99
SEAF	45°S–25°S	25°E–50°E	0.96/0.97	0.94/0.94	0.94/0.97	0.97/0.98
SEA	15°S–10°N	100°E–150°E	1.13/1.13	1.08/1.07	1.06/1.17	1.18/1.21
Global Oceans			1.01/1.01	0.99/1.00	1.00/1.01	1.00/1.01

<sup>a</sup>Northwest coast of Africa (NAF); Indian Bay of Bengal (IBB); Coastal China (CHN); Central America (CAM); Arabian Sea (ARS); Mediterranean Sea (MED); Southwest coast of Africa (SWAF); Southeast coast of America (SCA), and Southeast Asia (SEA). For each table entry with  $f_r$  values, the first number represents the seasonally averaged  $f_r$  from the 2006 study period (Mar. 2006–Feb. 2007), and the second number after back-slash represents the seasonally averaged  $f_r$  from the 2007 study period (Mar. 2007–Feb. 2008).





**Figure 3.** The RGB true color composite from Aqua MODIS for August, 16, 2006. Red and green dots are GOES and MODIS detected fires respectively. The contour lines are the daily averaged NAAPS 24-h AOD.

presented by Reid *et al.* [2004]. In both cases, there are sufficient MODIS aerosol retrievals available ( $>100$  data entries/3 month) and hence low data sampling rate is not a likely cause of this perceived bias. However, the Reid *et al.* [2004] analysis used a free running model with a known 50% low bias over land. Consequently, in our case the comparison of known high AODs behind a front to lower AODs assimilated from MODIS may result in an underestimate in the magnitude of our perceived bias.

### 3.3. Contextual Bias in SE Asia and Indonesia

[17] Unlike the southern oceans, we found a strong positive bias in SE Asia and Indonesia of nearly 30% in all four seasons. Beside the cloud contamination issues [Zhang and Reid, 2006; Tian *et al.*, 2008], like the rest of the tropics, the region received significant precipitation, particularly in the months of January through July. The intervening dry season shows a marked increase in fire activity as well as more longevity of pollution emissions. Thus, we would indeed expect that cloudy conditions to covary with precipitation and hence scavenging and thus observations would be biased high. This perceived bias however is more complicated in that the model's smoke emissions are based on fire hot spot data which also requires clear skies. While we believe that this circular bias is not of significant consequence, it does illustrate the difficulty in determining regional aerosol burdens.

### 3.4. Remote Southern Oceans

[18] Lastly, in order to gain insight into the contested positive correlation between cloud fraction and AOD we performed simulations of  $f_r$  over remote oceans that are far from any major pollution sources [Zhang and Reid, 2006]. Since the total aerosol concentrations are very small over remote oceans, we repeated the exercise mentioned before but using NAAPS natural runs instead of assimilation + forecasts. By doing so, we try to avoid small-scale AOD noise that is introduced by the aerosol data assimilation process and relies heavily on the model's sulfate and sea salt component of Christensen [1997] and Witek *et al.* [2007], respectively.

[19] For the period of March 2006–February 2007, over high latitude southern ocean that have persistent cloud cover and low data sampling rate from MODIS, we found a averaged low  $f_r$  value of 0.8–0.9. This suggests that AOD

values over cloudy regions could be higher than over clear regions, although by a very small amount of less than 0.02, relative to the typical AOD of 0.1 for the region [Smirnov *et al.*, 2006]. The higher AOD values under cloud decks could be caused by high humidity and/or cloud-wind-sea salt interactions, and should be investigated in the future research. Regardless this exercise reinforces the findings of Zhang and Reid [2006] that the bulk of the satellite AOD-cloud cover relationship is indeed mostly artifactual in the remote oceans due to leakage in the cloud mask.

## 4. Conclusion

[20] Using two years of the NAAPS AOD product with MODIS optical depth assimilation, we estimated the clear sky, contextual, and/or sampling biases in the operational MODIS level 2 collection 5 aerosol products. Our main conclusions are:

[21] 1. MODIS-derived global over-ocean AOD climatologies show a negligible bias of less than 5% at the seasonal and even monthly level. This lack of global bias is a result of offsetting positive and negative zonal biases in the tropics and mid latitudes, respectively.

[22] 2. In some aerosol prevalent regions, biases are still typically within  $\pm 10$ –20%.

[23] 3. The largest negative departure was a  $-30\%$  bias off of the southeastern coast of South America and Africa, due to transport covariance of biomass smoke behind fronts.

[24] 4. The largest positive departure was  $+30\%$  in Southeast Asia and Indonesia region due to lower aerosol burdens under clouds, likely due to wet scavenging. Cloud cover also restricts observation of fire activity, which may introduce a reduction in perceived bias.

[25] 5. Our study suggests that over remote clean oceans, model-derived all-sky aerosol optical depth is only 10–20% greater than the clear sky MODIS/sun-photometer retrieved counterpart, or less than 0.02. This negligible increase supports previous work by Zhang and Reid [2006] that most of the high AOD observed in the Southern ocean are retrieval artifacts.

[26] 6. Ultimately, these findings indicate that for long-term comparisons between satellite and model data, assuming clear sky is representative of the mean is mostly justified. However, on a regional scale, sampling related biases could

not be neglected for aerosol studies using satellite aerosol products.

[27] **Acknowledgments.** This research was funded by the Office of Naval Research Code 322, the Office of Naval Research Young Investigator Program, and the NASA Interdisciplinary Science Program. We thank Cindy Curtis of NRL for her help processing data and imagery for this study.

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